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13. ABSTRACT (Maximum 200 Words) Many animals, ranging from bacteria, through nematodes, to insects, fish and mammals, use air- or water-borne plumes of odor molecules to locate distant unseen resources. We have used our knowledge of the well studied pheromone plume tracking behavior of male moths, as the foundation for simulation and robotic experiments aimed at learning more about the mechanisms underlying biological systems. We extended this knowledge to engineering approaches to generate an autonomous artificial agent that is able to track chemical plumes through complex environments. We have developed simulation models and robotic control systems that adapt their performances to the local odor and wind environment and perform more successfully than those that do not adapt. Algorithms that use Bayesian estimation adapt their performances to the width of the odor plume and "home-in" on the odor source in a manner similar to the behavior of flying moths tracking odor plumes. Mobile robot odor tracking experiments show that simple steering algorithms are more successful at locating the odor source than those with internal models of the wind sensing system.			
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FINAL REPORT

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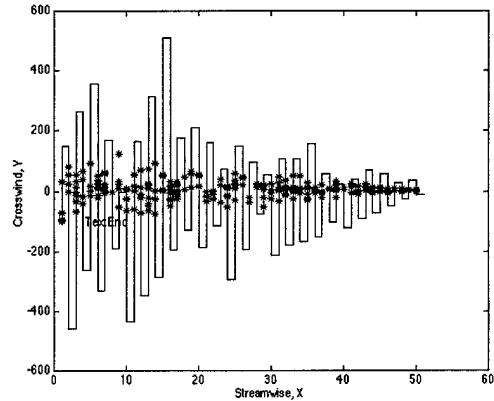
Objective: My objective is to develop and test guidance algorithms for tracking chemical plumes: first, by using simulation models based explicitly on the odor-guided navigation behavior of flying insects, and second by testing these algorithms in plume tracking robots.

Approach: Computer simulation models of odor-guided navigation have been implemented in C+, MatLab, and LabView, and challenged to track a variety of different plumes in simulated environments. The simplest environments are models of our laboratory wind tunnel where we study the behavior of male moths tracking plumes of female sex-attractant pheromones. More complex simulations include continuously changing wind conditions and variable plume structures that more closely approximate the field environments where moths would normally perform plume-tracking behavior. Successful simulation approaches have now been implemented in small mobile robots in our laboratory wind tunnel using ionized air as the model plume. By using this model, we achieve a plume detectable with easy to use sensors, that can be switched on anytime. The ion antennae are also similar in size to the olfactory antennae of the moth we study. Candidate plume tracking algorithms are programmed in LabView and run on a desktop PC connected to the robot.

Accomplishments:

- 1) *Simulation modeling of plume tracking experiments:*
 - Adapted existing biologically-based model to be more flexible and include sensory processing modules.
 - Initiated new analytical modeling approach in which behavioral decisions and adaptation of ongoing tracking behavior are based on a Bayesian statistical description of the odor plume.
 - Models based on Bayesian estimation result in moth-like behavior in odor tracking simulations run against simple simulated plumes (Fig. 1).

Figure 1. Plume tracking performance of an analytical model that makes decisions on when to turn using Bayesian statistics of the odor plume. Red line is model moth track, and blue asterisks represent the simulated odor plume. Note that the moth track "homes-in" on the odor source as it approaches - a behavior not produced by other models without Bayesian statistics.



- Altering the Bayesian model's parameters reveal that a slow steady counterturning strategy tracks the plume to the source more frequently than an algorithm with "faster" movement settings.
- A new more complex sensory system was applied to our earlier biologically-inspired algorithms. In this experiment the use of the ratio of peak to mean concentration of odor as plume information used for decisions about turning and movement velocity. This is the only experiment in the Chemical Plume Tracing Program to go beyond using the plume data sets collected in flumes as a simple binary signal (i.e., odor present or absent). Interestingly using this information as the basis for plume tracking behavior yielded lower success rates than other simpler strategies, suggesting that other characteristics of the plume may be more "useful" or that a suite of parameters is necessary to provide enough information to make reliable navigation decisions. Alternatively, one could imagine incorporating our Bayesian model's strategy of adapting your behavior based on previous experience with this more complex sensory processing to yield a more adaptable and reliable tracking algorithm.

2) *In support of the overall Plume Tracing Program:*

We video recorded chemical smoke plume visualizations of air-borne plumes in our laboratory wind tunnel. Smoke plume structure was recorded in different flow velocities and in turbulence designed to mimic flow in natural environments. These recordings were then digitized and posted for use by all other participants in the DARPA/ONR Plume Tracing Program. These digitized data sets were used by simulation and robotic projects based at U.C. Riverside and Cal Tech as well as this project.

3) *Plume tracking experiments with mobile robots:*

- Odor tracking simulation models written in Labview were first used to test ideas about steering control in *simuluo*, and then adapted as control software for our mobile robot.
- We developed miniaturized plume and wind direction sensors and software to interface the sensors with our small mobile

robot.

- Our first robotic experiment supports earlier simulation work showing that algorithms that generate countercurrents with inter-turn legs oriented more across the wind are more successful at source location than algorithms with inter-turn legs aimed more upwind. Furthermore, algorithms that modulate their turn magnitude and inter-turn steering according to local plume concentration are as successful as the most successful algorithm, but much faster at locating the source (Fig. 2).
- Seemingly "simple" algorithms for steering with respect to the wind are more successful at source location than those with "internal models" of the wind direction sensor.

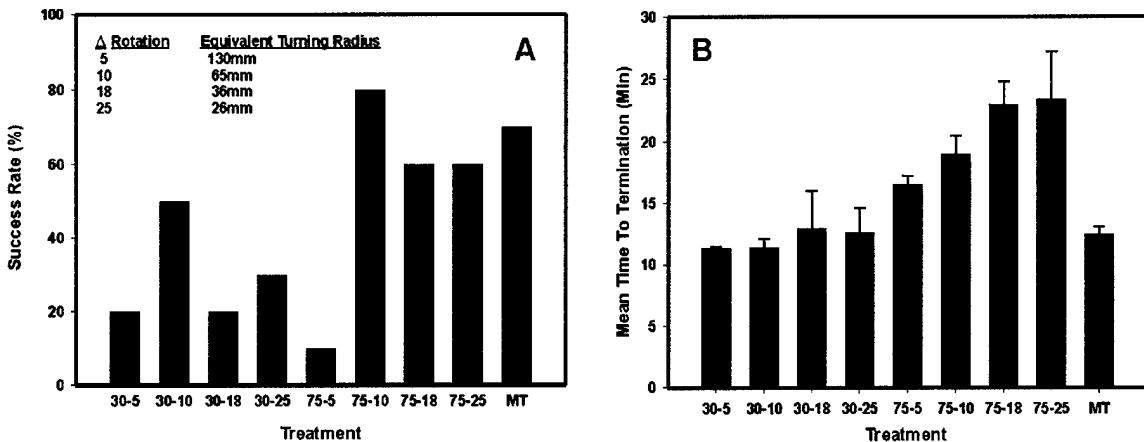


Figure 2. Plots of the success rate and mean times from initiation to termination of a robot plume tracking performance. (A) The success rate of robot plume tracking performances using different combinations of straight leg bearing angles and turning radius. (B) The mean time from initiation to termination of the same plume tracking performances depicted in Figure 4A above. In both plots the performances of the robot controlled by the algorithm that was modulated by plume concentration is depicted in red and labeled MT (Modulated Track).

Conclusions:

- Simulation models with control algorithms using Bayesian estimates of plume location are successful at locating targets and adapt their behavior according to local conditions.
- Both simulation and mobile robot experiments revealed a trade-off between speed and accuracy in locating sources of chemical plumes: slower algorithms locate sources more reliably, while faster algorithms traverse the plume faster but miss the source.
- Preliminary simulation experiments show that algorithms that use finer scale plume information do not perform better than simpler algorithms.
- Robot studies show that adaptation of steering and turning behavior according to locally detected plume concentrations leads to rapid plume tracking performances that are very

- successful at locating the source.
- Simulation studies show that the size of the radius of detection affects both success at source location and search time.
- Robot studies show that simple wind-based steering algorithms are more successful at locating the odor source than more complex internal model-based steering algorithms.

Significance: The biological significance of this project has been to test hypotheses about the mechanisms underlying odor tracking behavior in animals using methods not previously used. The significance of this project to the goals of the U.S. Navy may be many fold. The results of our work could form the foundation of autonomous chemical tracking systems with the ability to locate targets hidden to more conventional visual or electromagnetic detection systems. Furthermore, by using a flying animal as a basis for our work we have generated algorithms that can be used in any fluid environment; i.e., air or water.

Patent Information: We have not applied for any patents.

Award Information: I have been hired from my position as a research scientist at the University of Arizona to become a tenure-track associate professor in the Biology Department at Case Western Reserve University, Cleveland, Ohio.

Publications and Abstracts (for total period of grant):

Belanger, J.H., Willis, M.A. and Jouse, W.C. (2001) A combined approach of simulation and robotic studies to the problem of understanding animal orientation to odor plumes. International Congress of Neuroethology.

D. Grünbaum and M.A. Willis. Spatial memory-based behaviors for locating sources of odor plumes: Simulation studies of pheromone responses in *Manduca sexta*. (in prep. for Journal of Comparative Physiology A).

J. Belanger. Simulation studies of odor plume location, tracking and source location. (in prep. for Adaptive Behavior).